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TITLE MECHANICAL PROPERTIES OF LUNAR MATERIALS UNDER ANHYDROUS, HARD VACUUM CONDITIONS: APPLICATIONS OF LUNAR GLASS STRUCTURAL COMPONENTS

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MECHANICAL PROPERTIES OF LUNAR MATERIALS UNDER ANHYDROUS, HARD VACUUM CONDITIONS: APPLICATIONS OF LUNAR GLASS STRUCTURAL COMPONENTS

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Short Title:

J. D. Blacic: Mechanical Properties of Lunar Materials.

ABSTRACT

Lunar materials and derivatives such as glass may possess very high tensile strengths compared to equivalent materials on Earth because of the absence of hydrolytic weakening processes on the Moon and in the hard vacuum of free space. Hydrolyzation of Si-O bonds at crack tips or dislocations reduces the strength of silicates by about an order of magnitude in Earth environments. However, lunar materials are extremely anhydrous and hydrolytic weakening will be suppressed in free space. Thus, the geomechanical properties of the Moon and engineering properties of lunar silicate materials in space environments will be very different than equivalent materials under Earth conditions where the action of water cannot be conveniently avoided. Possible substitution of lunar glass for structural metals in a variety of space engineering applications enhances the economic utilization of the Moon.

INTRODUCTION

The subject of this paper is the effects of the environmental conditions of the Moon and free space on the mechanical properties of lunar rocks and materials derived from them. The thesis of the paper is that mechanical properties of silicate materials are very different in the anhydrous, hard vacuum conditions of space compared to Earth due to the virtual absence of hydrolytic weakening processes there. We believe that the implications of this realization will be very important in the interpretation of geophysical measurements to investigate the structure of the Moon, in exploitation of lunar materials for construction of a lunar base, and in eventual space industrialization and habitation.

After documenting what is currently known about these environmental effects, we concentrate in this paper on the implications of "anhydrous strengthening" of an easily formed structural material derived from lunar regolith, namely lunar glass. Although the potential importance of lunar-derived glass has been known for some time (Phinney et al., 1977), the full implications of the potentially very great strength of lunar glass in the vacuum environment are not widely realized. In detailing some applications of lunar glass structural components, we have in mind a philosophy that requires maximal utilization of common lunar materials with minimal processing before end use. It has become clear that large-scale exploitation of space is limited by the cost of Earth-lift of materials. Therefore, it is essential that every possible means be taken to utilize indigenous materials from the Moon and, eventually, the asteroids. In doing so, we should not fight the *in situ* environmental conditions (e.g. low gravity, vacuum), trying to wedge

Earth-derived processes into conditions for which they are not adapted; rather, we should attempt to take advantage of what we are given in new ways. It is in this sense that we believe that lunar glass can play a central role in easing our full-scale entry into the new frontier of space.

HYDROLYTIC WEAKENING PROCESSES IN SILICATES

It has been known for some time that the fracture strength of brittle amorphous and crystalline silicates is determined in Earth environments by the damage state of surfaces and, most especially, the corrosive action of water in extending microcracks (Charles, 1958; Scholz, 1972). For example, the moisture sensitivity of glass is well known. Merely touching freshly-formed glass rods will drastically reduce their tensile strengths, and less than one percent of the theoretical tensile strength of glass is normally realized in industrial practice (LaCourse, 1972). Similarly, the plastic strengths of crystalline silicates (e.g. quartz and olivine) at elevated temporatures and pressures are strongly affected because trace amounts of water aid dislocation motion (Griggs, 1965; Blacic, 1972). In both instances, the weakening mechanism is believed to involve the hydrolyzation of Si-O bonds (Griggs, 1967; Blacic and Christie, 1984; Charles, 1959; Michalske and Freiman, 1982). A schematic representation of one proposed mechanism is shown in Figure 1 (Blacic and Christie, 1984). The great inherent strength of silicates is due to the strength of the network-forming silicon-oxygen bonds. However, it appears that the polar water molecule can easily hydrolyze these linking bridges by replacing the strong Si-O bond with an order of magnitude weaker hydrogen-bonded bridge. This hydrolyzation can occur along dislocations, thereby increasing the mobility of dislocation kinks, or at highly stressed microcrack tips resulting in a lower applied stress to propagate the cracks. In both cases, the net result is a large weakening of the material when even very small amounts of water are present.

Whatever its detailed nature, the hydrolytic weakening mechanism is demonstrably a thermally activated rate process. Thus, the time- and temperature-dependent mechanical properties of silicates (brittle and plastic creep, static fatigue, subcritical crack growth) are dominated by moisture effects (Charles, 1958; Scholz, 1972; Blacic and Christie, 1984). As might be expected, these hydrolytic weakening processes are an important factor in such diverse areas as solid earth mechanics, geotechnology (drilling and mining), materials science (glass and ceramic technology), communications (fiber optics), national defense (high energy laser optics), and others--since, on Earth, it is practically impossible to avoid the presence of some water in the fabrication or use of materials be they natural or synthetic. However, the case may be much different on the Moon and in free space.

ANHYDROUS STRENGTHENING ON THE MOON?

Although there is still hope that we may find some water preserved in the permanently shaded regions of the lunar poles (Arnold, 1979), a striking feature of all lunar materials examined so far is their almost total lack of water (Handbook of Lunar Materials, 1980). The very small amount of water that is observed to evolve from heated lunar samples is likely due to either oxidation of solar wind-implanted hydrogen [present at about the 100ppm level (Handbook of Lunar Materials, 1980)] or is the result of Earth contamination

(Carrier et al., 1973). There is no unequivocal evidence of native water in any lunar sample returned to date. This fact suggests that in the hard vacuum of space silicates derived from the Moon will not, if we can avoid contaminating them, exhibit the water-induced weakening that is so ubiquitous on Earth. In other words, lunar silicates may possess very high strengths due to an "anhydrous strengthening" effect relative to our common experience on Earth. This possibility has numerous implications for space industrialization, some of which are explored below.

There is some supporting laboratory evidence for the anhydrous strengthening phenomenon in lunar or lunar-simulant materials. The compressive strength of a mare-like simulant rock (basaltic intrusive) has been shown to increase by about a factor of two when samples are degassed and tested in a moderate laboratory vacuum compared to tests in 100% humid air (Mizutani et al., 1977). Subcritical crack velocity measurements in a lunar analogue glass demonstrate many orders of magnitude reduction in crack velocity with decreasing partial pressure of water (Soga et al., 1979). This suggests that static fatigue processes will be strongly suppressed or absent in lunar materials in a vacuum environment. Several investigators have found that very small amounts of water strongly affect the dissipation of vibratory energy (Q^{-1}) in lunar and terrestrial rocks (Pandit and Tozer, 1970; Tittmann et al., 1980). These attenuation mechanisms are likely the result of the hydrolyzation of crack surfaces with consequent reduction of surface energy in a manner similar to Figure 1. The soil mechanics properties of Apollo samples and simulants have been shown to be strongly affected by atmospheric moisture contaminants in moderate and ultra high vacuum experiments (Carrier et al., 1973; Johnson et al., 1973). These latter results suggest that well-consolidated lunar regolith may be substantially stronger than similar materials on Earth with important implications for energy requirements for handling of lunar materials.

There are many additional examples, too numerous to document here, of research on the effects of water on the mechanical properties of terrestrial silicate materials. The main conclusion to be gained from all this work is that water, even in trace amounts, is all important in explaining the great reduction in strength of silicates. However, in order to get some quantitative estimate of the possible increase in strength of lunar materials relative to their Earth counterparts, it is instructive to examine in some detail the elegant results of F. M. Ernsberger (1969) on glass.

In Ernsberger's experiments, etched glass rods are heated and deformed to produce entrapped bubbles in the form of oblate spheroids. The bubbles concentrate stress at the point of maximum curvature of the bubble-glass interface in a calculable way. In addition, if care is taken, failure always occurs at the flaw-free bubble surface where the atmosphere is constant and relatively anhydrous. Using this technique, Ernsberger was the first to achieve controlled compressive failure of glass by shear fracture or densification. Scatter in tensile strength measurements was reduced compared to normal test methods; results are shown in Figure 2 for soda-lime glass. The temperature dependence of strength shown in Figure 2 is believed to be due to solid-state diffusion of weakening elements to the stress concentration, possibly sodium but more likely residual water dissolved in the glass. At reduced temperatures, the weakening element is immobilized and strength increases. The important aspect of this work, confirmed by other investigators for other glass compositions, is that the strength is about an order of magnitude higher in an anhydrous environment than it is for the same glass tested in a normal humidity atmosphere. This gives some idea of what might be expected for a lunar glass used in vacuum, although it probably represents only a minimum strength estimate because of the extremely anhydrous nature of lunar materials and the hard vacuum of space.

SOME POSSIBLE APPLICATIONS

Table 1 compares the mechanical properties of some structural metals likely to be produced from lunar regolith with estimates for lunar glass. Common soda-lime glass under Earth conditions is also listed for comparison. The range of tensile strength estimated for lunar glass is believed to be conservative, as discussed above, but even if only the low end of the range can be achieved, then one can see that lunar glass is very competitve with--if not superior to--the metals obtainable from lunar materials with considerably more processing effort.

How can lunar glass be utilized? One obvious way is in the form of glass fibers in tensile stress situations. Although lunar glass will be very strong, it will still be a very brittle material and therefore it makes sense to distribute the load over many small elements whenever possible. Thus, lunar glass fiber cloths (Criswell, 1977) and multiply-stranded cords and cables should see wide application in a lunar base and large space structures such as solar power satellites (SPS). However, we believe that lunar glass fibers should always be coated with a metal such as Fe, Al, or Mg to protect the glass from inadvertant or purposeful exposure to water vapor. Otherwise, a highly stressed glass component might fail catastrophically due to water-induced stress corrosion. The metal coating could easily be incorporated into the production process and would also serve the desirable purpose of protecting the fibers from mechanical damage during production handling or use. This is commonly done in terrestrial fiber glass production in the form of organic sizing coatings.

Figure 3 schematically shows the elements we believe will be required in a lunar or space-based glass fiber production plant. We have assumed that sufficient electrical energy will be available [alternatively, direct solar melting could be used (Ho and Sobon, 1979)] and that there will be at least some minimal beneficiation of the feed stock. We believe that no lunar or space-based processing plant should be without some means of capturing the rare but highly valuable volatile elements in the lunar regolith. We also suggest in the figure that the relatively new Pochet-type furnace (Loewenstein, 1973) be investigated for use in lunar glass production because of the advantage it would seem to have in weight over traditional furnaces.

For applications requiring flexural, compressive, or mixed loadings such as for bulkheads in a habitat or beams and columns in an SPS, fiber glass composites would be advantageous. Of the many types of composite materials seeing increasing terrestrial usage, two would be especially attractive for space applications: metal matrix and ceramic matrix composites. Gas-tight metal matrix composites such as graphite-aluminum are now widely used in aerospace applications. If we follow our philosophy of minimal processing of lunar materials before end use, then lunar glass fiber (LG)-Fe matrix composites should be developed since native iron will be available from regolith beneficiation for fiber coating in any case. The lunar vacuum would make the diffusion bonding and liquid metal infiltration techniques (Davis and Bradstreet, 1970) of composite production advantageous. We believe that this lunar glass-metal matrix composite would be very useful in lunar-base habitat construction. If a lighter weight composite is wanted, for example for SPS applications, then silica fiber-Mg composites could be produced when a more sophisticated processing capability becomes available.

Ceramic matrix composites offer some special advantages in certain applications. Large space structures such as antennas and support structures of an SPS are sensitive to the potentially large thermal strains associated with periodic eclipses. Table 2 lists thermal expansion coefficients for some structural materials. Note that glass generally has lower thermal expansivity than common structural metals and also that some compositions derivable from abundant lunar materials (e.g. titanium silicate glass) exhibit extremely low thermal expansion. If one were willing to import from Earth small amounts of graphite fiber (which has a negative thermal expansivity), then composites having zero thermal expansion could be produced (Browning, 1982). Ceramic matrix composites exhibit one other desirable property. If the reinforcement fibers do not chemically bond to the ceramic matrix but instead are held dominantly by frictional forces, then the composite exhibits an enhanced ductility and residual strength beyond the yield point to relatively large strains and is notch insensitive in a manner similar to metals (Evans, 1984). Thus, we envision a composite in which Fe coated LG fibers are imbedded in a lunar glass matrix. Such a material may have very desirable structural entirely from the most common lunar materials with the least amount of processing.

Finally, we would like to support the suggestion of Rowley and Neudecker (1984) that lunar habitats be formed by melting in-place glass-lined tunnels using the SUBTERRENE (perhaps in the present context better termed "SUBSELENE") technology. If the glass-lined tunnels were sputter coated with a metal to protect the glass from water vapor and if the LG fiber composites were used for bulkheads, etc., then extensive lunar habitats with more than adequate radiation shielding from the largest solar flare storms could be produced from 100% lunar materials. No doubt engineers and architects will find many more uses than we have thought of for a light-weight structural material with several hundred thousand psi tensile strength.

RESEARCH NEEDS

Most of what we have advocated concerning the possible high strength of lunar materials in hard vacuum environments has been based on research of terrestrial silicates under terrestrial or at best poorly simulated space conditions. Ultimately, our contentions must be proved at full-scale using actual lunar materials under in situ conditions. A lunar-based materials testing laboratory would seem necessary for this and should be an early, high priority lunar-base facility. Until reoccupation of the Moon, however, much can be learned and perhaps our basic contentions proved by experiments using lunar simulants formed and tested under ultra high vacuum laboratory conditions on Earth. This approach would seem initially preferable to LEO shuttle experiments because of the relatively poor vacuum environment of the shuttle resulting from the normally low orbits achieved and, perhaps more importantly, outgassing of the vehicle itself. Perhaps the free flying or tethered experimental platforms proposed in conjunction with the space station will improve this situation and will be needed to evaluate the effects of extended exposure to radiation and micrometeoroid fluxes, but for now ultra high vacuum experiments in Earth laboratories appear most appropriate. Most urgently needed are basic mechanical properties such as tensile and compressive strengths, fracture toughness, and thermal properties. With these results in hand, investigation of potential composite materials can proceed followed by bench top and prototype engineering of the manufacturing facilities that will be required. Also, research and evaluation of the "SUBSELENE" approach to lunar habitat formation should proceed because of the advantages it would seem to have over imported structures.

SUMMARY

Although the apparent absence of water on the lunar surface causes difficulties for many of the things we would like to do on the Moon, in one respect at least it may be a blessing. It appears that the anhydrous, hard vacuum environment and the inherently dry nature of lunar regolith materials down to the ppb level make possible the use of lunar glass for structural applications that would be impossible on Earth. In view of the fact that the initial cost of large-scale industrialization and scientific exploitation of the space environment is dominated by Earth-lift requirements, the possible extensive use of lunar glass structural materials in a wide variety of applications offers promise of very large savings in Earth export expenses and thereby enhances the economics of utilizing the Moon. From a purely scientific point of view, it is likely that the anhydrous strengthening phenomenon will have numerous implications for a wide range of geological and other scientific investigations on the Moon in which mechanical properties play an important role.

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Table 1. Mechanical Properties of Lunar-Derived Materials.

	T (GPa/10^6 psi)	ρ	E (GPa/10^6 psi)	T/ρ (GPa/10^6 psi)	E/ρ (GPa/10^6 psi)
ALUMINUM	0.17/0.02	2.7	70/10.2	0.06/0.009	25.9/3.76
MAGNESIUM	0.20/0.03	1.7	45/ 6.5	0.12/0.017	26.5/3.84
IRON	0.28/0.04	7.9	196/28.4	0.04/0.006	24.8/3.60
TITANIUM	2.3 /0.33	4.6	119/17.3	0.50/0.073	25.9/3.76
ALLOY STEEL	2.3 /0.33	8.2	32/ 4.6	0.28/0.041	3.9/0.57
SODA-LIME GLASS (EARTH ENVIRONMENT)	0.07/0.01	2.5	66/ 9.9	0.03/0.004	27.2/3.95
LUNAR GLASS (SPACE ENVIRONMENT)	0.01/0.01-3.0/0.44 or greater?	2.8	100/14.5 ?	0.25/0.036-1.07/0.155	35.7/5.19 ?

T = ultimate tensile strength,
ρ = specific gravity,
E = Young's modulus.

Table 2. Thermal Expansion.

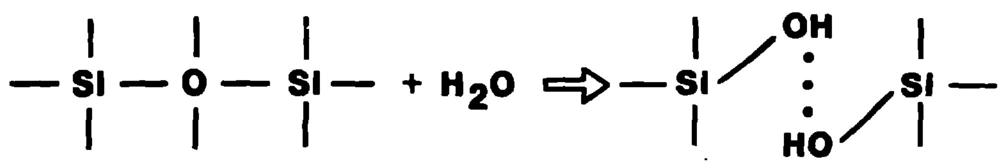
	$\Delta L/L$ (10^{-6} °C^{-1})
ALUMINUM	24.0
MAGNESIUM	25.0
TITANIUM	8.5
IRON	12.0
STEEL	12.0
INVAR	1.2
E-GLASS	4.8
CORNING #7971 TITANIUM SILICATE GLASS	0.03

FIGURE CAPTIONS

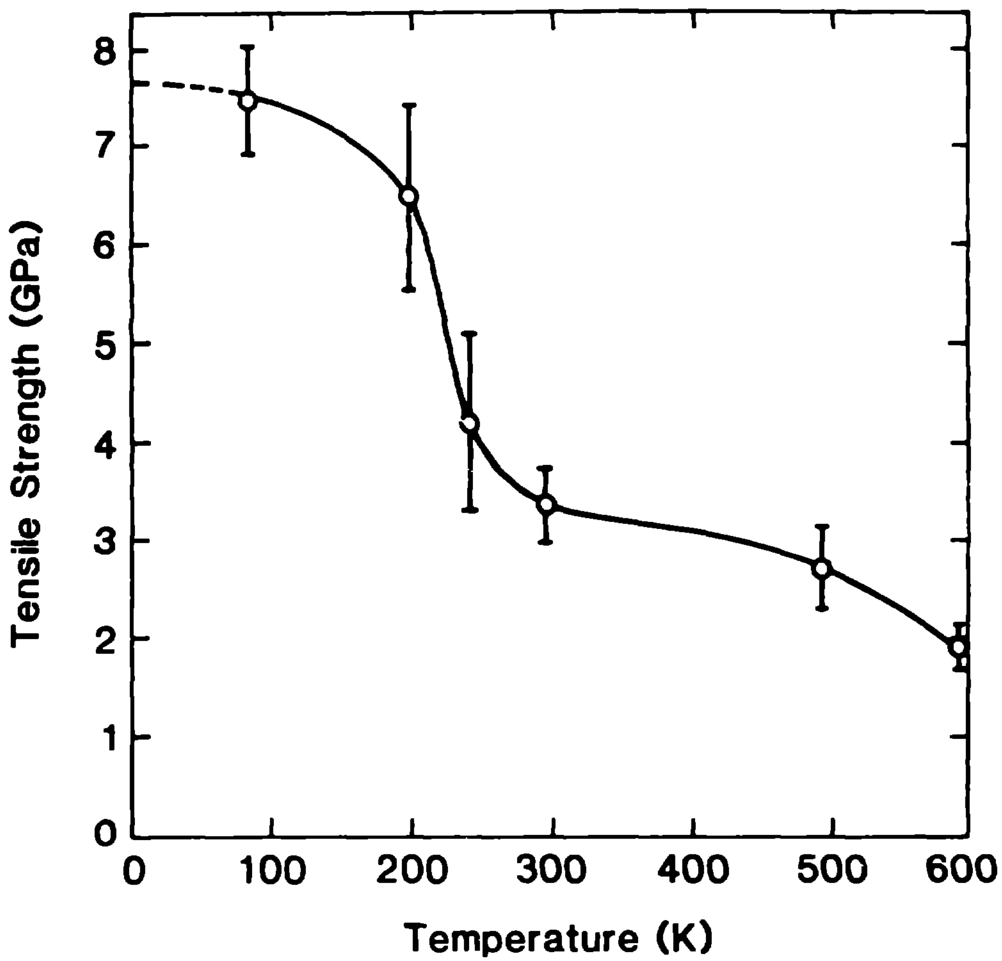
Figure 1. Schematic representation of the Si-O bond hydrolyzation reaction.

Figure 2. Tensile strength of Kimble R6 soda-lime glass in a relatively anhydrous environment as a function of temperature (Ernsberger, 1969)

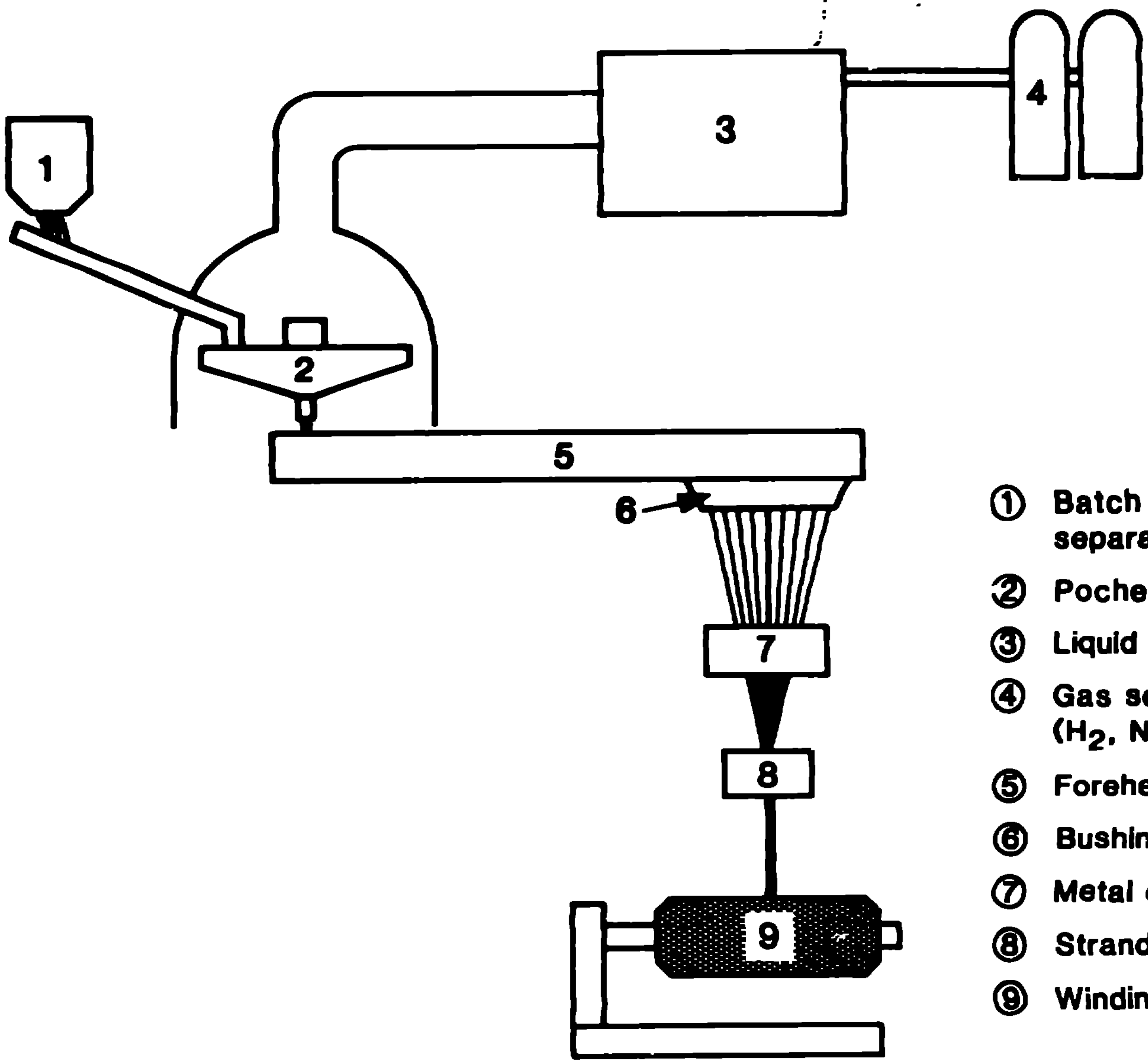
Figure 3. Elements of a lunar-base glass fiber and gas recovery plant.



⋮ = HYDROGEN BOND



Tensile Strength (GPa)
0
1
2
3
4
5
6
7
8
0
100
200
300
400
500
600
Temperature (K)



① Batch charging: magnetically-separated lunar regolith

② Pochet-type furnace

③ Liquid helium cryosorption pump

④ Gas separation and storage (H_2, N_2, C, He, Ar, S)

⑤ Forehearth

⑥ Bushing: Fiber formation

⑦ Metal coating evaporator

⑧ Strand formation

⑨ Winding: Strand take-up